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SRI Technical Report No. 21

Supplement To Special Technical Report No. 3

WASTE HEAT IN LIQUID SPHERICAL BURSTERS

Special Report

by

G. E. DUVALL

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Contract DA-18-035-AMC-122(A)

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SRI Project PAU-4900

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FOREWORD

The work described in this report was authorized under Task 1B522301A08101, Dissemination Investigations of Liquid and Solid Agents (U). The work was started in January 1967 and completed in August 1967.

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DIGEST

Special Technical Report No. 3 (hereafter referred to as STR-3) dealt with energy loss through shock heating in a bomblet with an explosive radius of 1.6 cm and an outer liquid radius of 3.85 cm. Detailed calculations were made for glycerin, water, and ethyl ether--the first and last representing practical extremes in the mechanics of organic liquid behavior.

In this supplement, attention is focused on the effects of changing burster size. The validity of linear scaling is examined and is found to be adequate to burster radii of 2.56 cm.

New equations of state are used for the three liquids mentioned above, and the sensitivity of waste heat to changes in the equation of state is examined. In addition, an error introduced in STR-3 near the explosive-liquid interface by the numerical integration process is corrected.

CONTENTS

ILLUSTRATIONS

TABLES

I IMPROVED EQUATIONS OF STATE

As noted on page 17 of STR-3, Eq. (25)* for the isotherms is unsatisfactory because of the inflection point at low pressures. This difficulty has been removed by fitting Hugoniot data to the form

$$P_H = a_1 m + a_2 m^2 + a_3 m^3 \qquad \text{(S1)}$$

where

$$m = (\rho/\rho_o) - 1 = (V_o/V) - 1$$

Using Eq. (S1), Eq. (20) was integrated numerically to obtain the 20°C isotherm. The values obtained through this integration process were used to determine by least squares the coefficients b_1, b_2, and b_3 for isothermal pressure:

$$P_i = b_1 m + b_2 m^2 + b_3 m^3 \qquad \text{(S2)}$$

Values of a_1 and b_1 for glycerin, water, and ether are given in Table S1.

Table S1

COEFFICIENTS FOR CALCULATING HUGONIOT AND ISOTHERMAL PRESSURE, (Mbar) [Eqs. (S.1) and (S.2)]

Liquid	V_o (cc/g)	b (g/cc)	a_1	a_2	a_3	b_1	b_2	b_3
Glycerin	0.795	0.977	0.04560	0.18572	0.39734	0.04035	0.20832	0.29888
Water	1.0018	0.107	0.02195	0.06878	0.20686	0.02181	0.07023	0.20059
Ether	1.405	0.527	0.00720	0.03693	0.08276	0.004619	0.042386	0.063185

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*In this supplement, equation, table, figure, and page numbers refer to STR-3, except where the number is preceded by an S (indicating "Supplement").

II WASTE HEAT CALCULATIONS

The results of calculations made with the new equations of state for the same geometry used in STR-3 are shown in Tables S2, S3, and S4 for glycerin, water, and ether, respectively. The ΔW used in these tables is an interface correction described below.

Specific waste heat versus radial index J is plotted in Figs. S1, S2, and S3. The point on the interface (J = 40) is obtained from independent calculation of the pressure induced in the fluid by explosive detonation. Low values of W_H near the interface arise from a well-known deficiency in the Q-method.* The smooth interpolation shown in the figures gives rise to a correction, ΔW, for total waste heat, W, shown in Tables S2 through S4; r_o in these tables and figures is the radial coordinate in the undisturbed material.

A second type of error arises near the interface, as illustrated in Fig. S4 for ether, which is the worst case.† This graph has been constructed by going through the results of flow calculations, picking the maximum pressure that appears in a cell and the temperature and specific volume that appear in the same cell at the same time, and plotting the former two against the last. Hugoniot calculations of pressure and temperature are made from the same equation of state, and the results are also plotted versus specific volume. The pressures agree fairly well; the low point at $V = 0.71$ may result from failure of the printout to show the maximum pressure in that cell. Temperatures obtained from flow calculations near the interface ($V \lesssim 0.78$ cc/g) are substantially higher than those from the Hugoniot calculations. The

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*Fyfe, Eng, and Young, SIAM Review 3 (October 1961).

†Since completion of this supplement, an error in the numerical program has been found. This contributed to the interface errors described above, and a test run has confirmed that the above procedure for correcting the waste heat is correct.

region of near agreement ($V \gtrsim 0.78$) is reached at about 10 cells from the interface ($r_o = 1.62$ cm), and no significant improvement is gained by decreasing the zone size, Δr_o. One might suspect this difficulty to arise from violation of the jump conditions in spherical geometry. However, the stress history of a single cell near the interface follows the Rayleigh line quite closely, and a calculation in plane geometry shows the same effect. It may be possible to reduce the error by rewriting the difference equations near the interface, but that will require considerable study. In any case, the graphical interpolation of W_H in Figs. S1 and S2 will correct for these computing problems.

New values of waste heat for the bomblet of STR-3 are summarized in Table S5.

Table S2

WASTE HEAT AND ENTROPY FOR GLYCERIN*
[r_o = 1.6 + 0.02 (J-41), cm]†

Cell No. (J)	ΔS (Mbar cc/g deg)	W_H (Mbar cc/g)	W_J (Mbar cc)	$W_J + \Delta W$§ (Mbar cc)
41	14×10^{-6}	5.683×10^{-3}	0.0047	0.0080
42	17×10^{-6}	7.000×10^{-3}	0.0105	0.0158
43	18×10^{-6}	7.744×10^{-3}	0.0172	0.0233
44	18×10^{-6}	8.044×10^{-3}	0.0243	0.0308
45	18×10^{-6}	8.018×10^{-3}	0.0315	0.0381
46	18×10^{-6}	7.778×10^{-3}	0.0387	0.0433
47	17×10^{-6}	7.445×10^{-3}	0.0458	0.0524
51	15×10^{-6}	6.053×10^{-3}	0.0720	0.0786
61	11×10^{-6}	3.912×10^{-3}	0.1270	0.1336
71	8×10^{-6}	2.731×10^{-3}	0.1724	0.1791
81	6×10^{-6}	1.972×10^{-3}	0.2112	0.2178
91	5×10^{-6}	1.469×10^{-3}	0.2448	0.2514
101	4×10^{-6}	1.122×10^{-3}	0.2744	0.2810
111	3×10^{-6}	0.872×10^{-3}	0.3007	0.3073
121	2×10^{-6}	0.689×10^{-3}	0.3242	0.3308
131	2×10^{-6}	0.551×10^{-3}	0.3455	0.3521
141	1×10^{-6}	0.447×10^{-3}	0.3647	0.3713
151	1×10^{-6}	0.366×10^{-3}	0.3822	0.3888
153	1×10^{-6}	0.352×10^{-3}	0.3855	0.3921

*This replaces Table VII of STR-3; explosive radius = 1.6 cm.

†r_o = inner radius of Cell J before shock arrival.

§ΔW = constant = 0.0066 Mbar cc for J $\geq$ 45. See text and Fig. S1.

Table S3

WASTE HEAT AND ENTROPY FOR WATER*
[r_o 1.6 0.02 (J-41), cm]†

Cell No. (J)	ΔS (Mbar cc/g deg)	W_H (Mbar cc/g)	W_J (Mbar cc)	$W_J + \Delta W$§ (Mbar cc)
41	26.9×10^{-6}	11.08×10^{-3}	0.0072	0.0137
42	31.7×10^{-6}	13.88×10^{-3}	0.0165	0.0263
43	33.8×10^{-6}	15.27×10^{-3}	0.0269	0.0381
44	34.2×10^{-6}	15.48×10^{-3}	0.0377	0.0493
45	33.4×10^{-6}	14.97×10^{-3}	0.0484	0.0600
46	32.1×10^{-6}	14.15×10^{-3}	0.0588	0.0704
47	30.1×10^{-6}	13.27×10^{-3}	0.0688	0.0804
51	25.8×10^{-6}	10.44×10^{-3}	0.1050	0.1166
61	18.1×10^{-6}	6.63×10^{-3}	0.1796	0.1912
71	13.0×10^{-6}	4.48×10^{-3}	0.2396	0.2512
81	9.6×10^{-6}	3.17×10^{-3}	0.2895	0.3011
91	7.2×10^{-6}	2.32×10^{-3}	0.3320	0.3436
101	5.5×10^{-6}	1.74×10^{-3}	0.3687	0.3803
111	4.3×10^{-6}	1.33×10^{-3}	0.4007	0.4123
121	3.4×10^{-6}	1.03×10^{-3}	0.4289	0.4405
131	2.7×10^{-6}	0.81×10^{-3}	0.4540	0.4656
141	2.2×10^{-6}	0.65×10^{-3}	0.4764	0.4880
151	1.8×10^{-6}	0.53×10^{-3}	0.4965	0.5081
153	1.7×10^{-6}	0.51×10^{-3}	0.5003	0.5119
161	1.5×10^{-6}	0.43×10^{-3}	0.5148	0.5264
171	1.2×10^{-6}	0.36×10^{-3}	0.5313	0.5429
176	1.1×10^{-6}	0.32×10^{-3}	0.5390	0.5506

*This replaces Table V of STR-3; explosive radius = 1.6 cm.

†r_o = inner radius of Cell J before shock arrival.

§ΔW = constant 0.0116 Mbar cc for $J \geq 45$. See text and Fig. S2.

Table S4

WASTE HEAT AND ENTROPY FOR ETHER*

[r_o = 1.6 + 0.02 (J-41), cm]†

Cell No. (J)	ΔS (Mbar cc/g deg)	W_H (Mbar cc/g)	W_J (Mbar cc)	$W_J + \Delta W$§ (Mbar cc)
41	18×10^{-6}	7.761×10^{-3}	0.0024	--
43	28×10^{-6}	16.413×10^{-3}	0.0158	--
45	29×10^{-6}	17.360×10^{-3}	0.0333	--
47	27×10^{-6}	15.576×10^{-3}	0.0503	--
49	25×10^{-6}	13.838×10^{-3}	0.0662	0.0791
51	24×10^{-6}	12.414×10^{-3}	0.0810	0.0939
61	18×10^{-6}	8.233×10^{-3}	0.1454	0.1583
71	14×10^{-6}	5.837×10^{-3}	0.2001	0.2130
81	11×10^{-6}	4.296×10^{-3}	0.2474	0.2603
91	9×10^{-6}	3.261×10^{-3}	0.2892	0.3021
101	7×10^{-6}	2.518×10^{-3}	0.3266	0.3395
111	6×10^{-6}	1.986×10^{-3}	0.3602	0.3731
121	5×10^{-6}	1.572×10^{-3}	0.3921	0.4050
131	4×10^{-6}	1.272×10^{-3}	0.4197	0.4326
141	3×10^{-6}	1.044×10^{-3}	0.4449	0.4578
151	3×10^{-6}	0.866×10^{-3}	0.4683	0.4812
153	3×10^{-6}	0.835×10^{-3}	0.4727	0.4856
161	2×10^{-6}	0.724×10^{-3}	0.4898	0.5027
171	2×10^{-6}	0.611×10^{-3}	0.5098	0.5227
181	2×10^{-6}	0.519×10^{-3}	0.5284	0.5413
191	2×10^{-6}	0.444×10^{-3}	0.5458	0.5587
194	1×10^{-6}	0.423×10^{-3}	0.5508	0.5637

*This replaces Table A1 of STR-3; explosive radius = 1.6 cm.

†r_o = inner radius of Cell J before shock arrival.

§ΔW = constant = 0.0129 for J $\gtrsim$ 49. See text and Fig. S3.

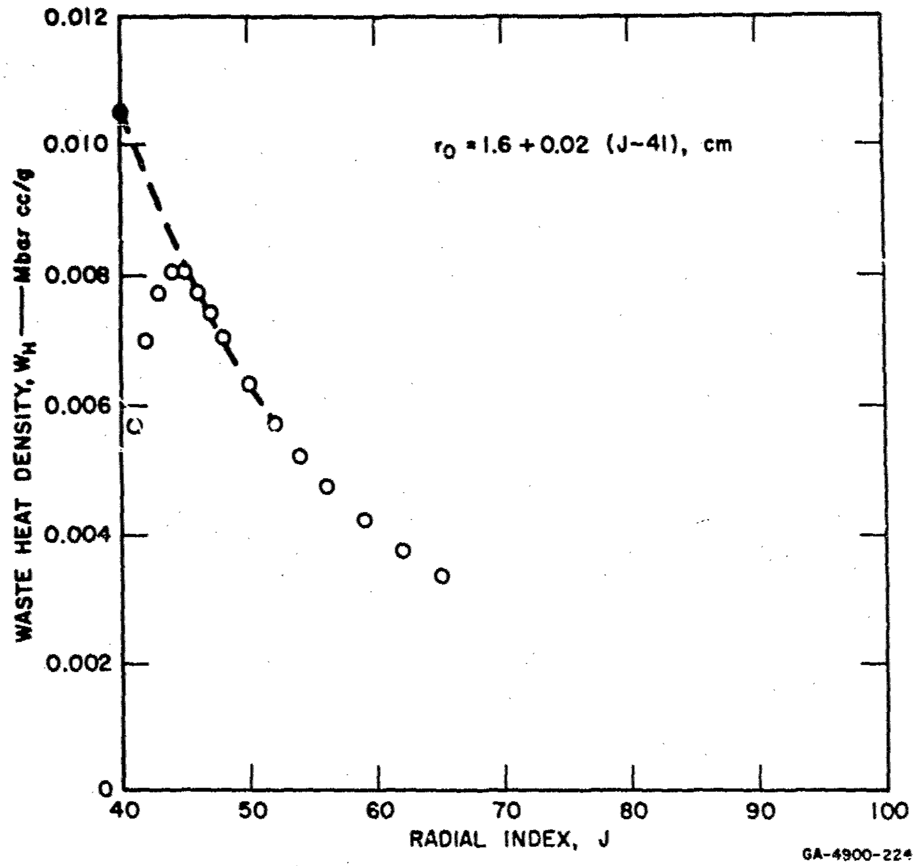

FIG. S1 WASTE HEAT DENSITY, W_H, VERSUS RADIAL INDEX, J, GLYCERIN

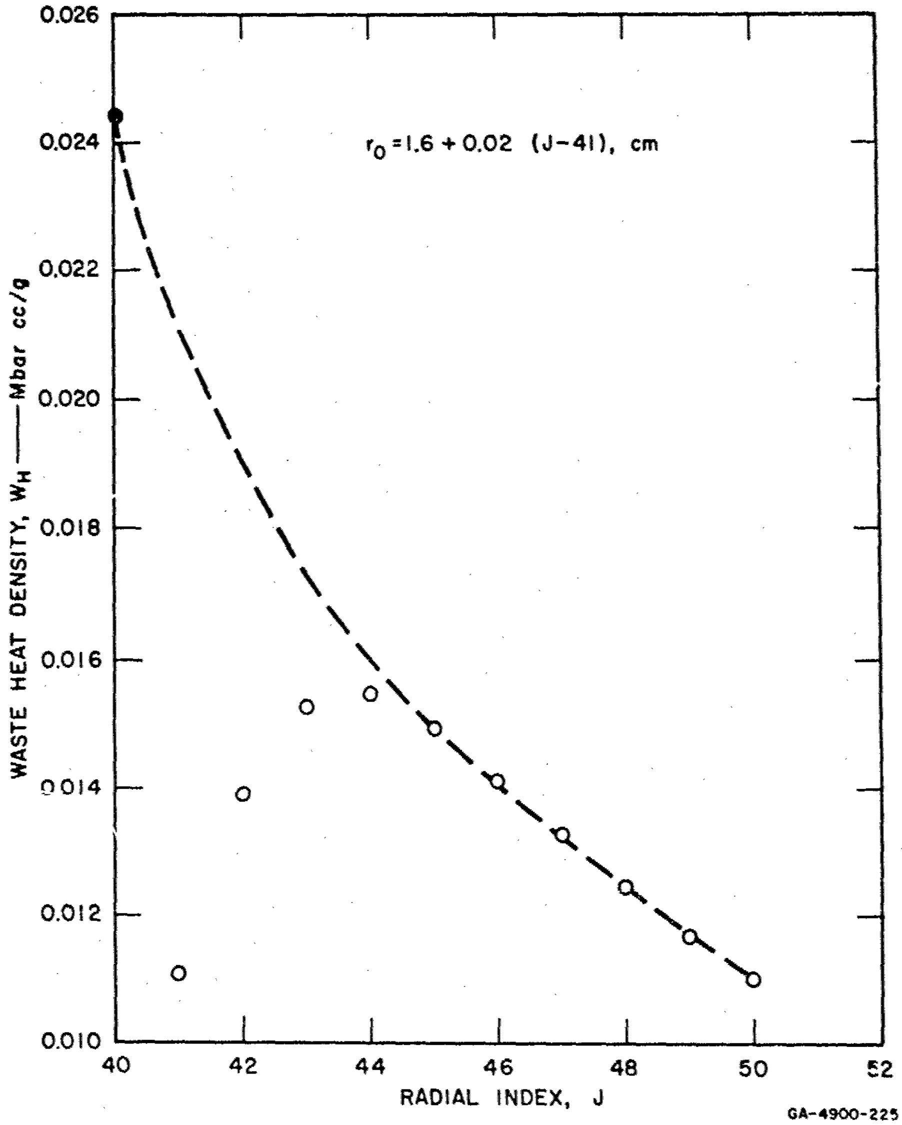

FIG. S2 WASTE HEAT DENSITY, W_H, VERSUS RADIAL INDEX, J, WATER

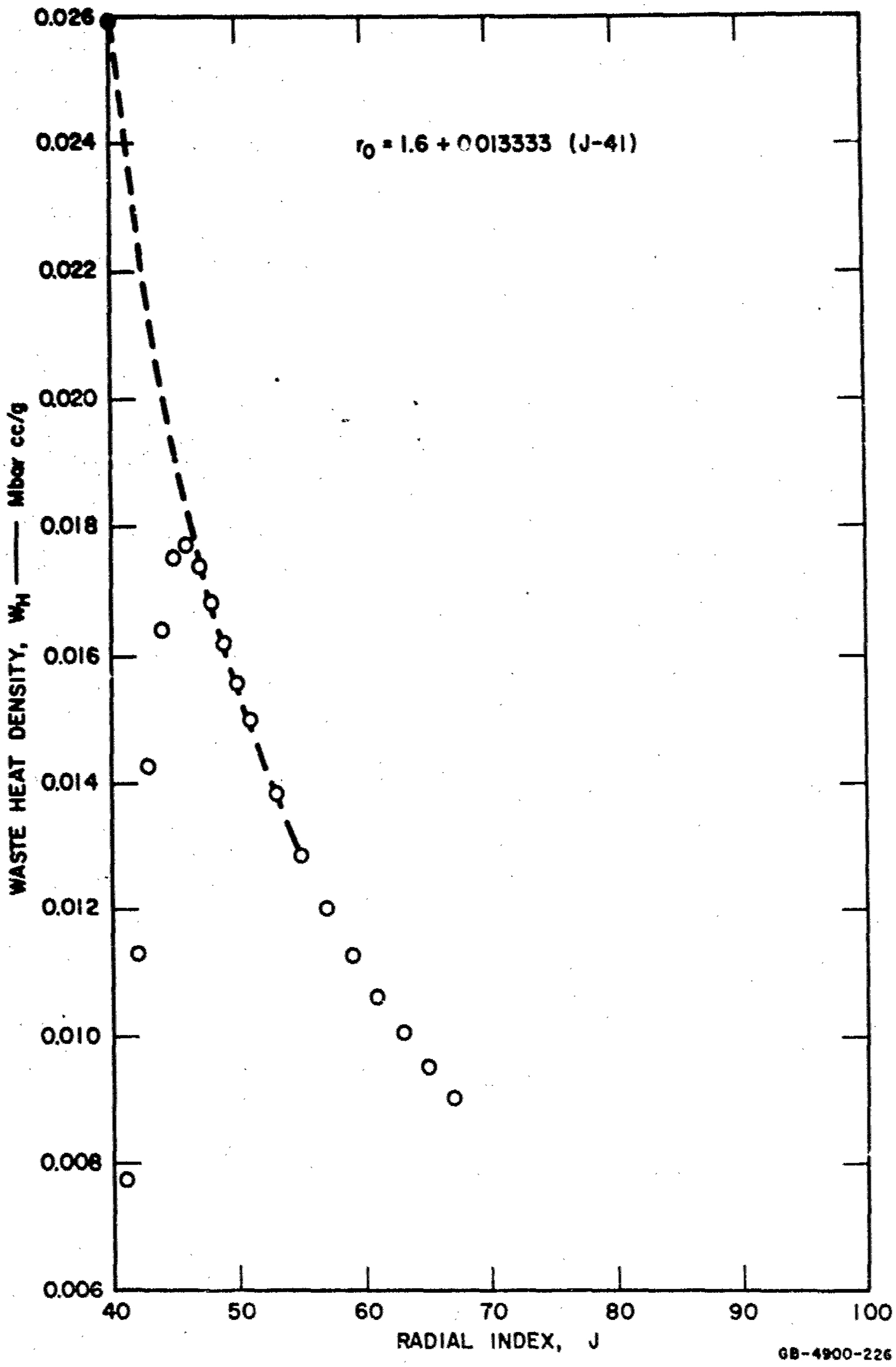

FIG. S3 WASTE HEAT DENSITY, W_H, VERSUS RADIAL INDEX, J, ETHER

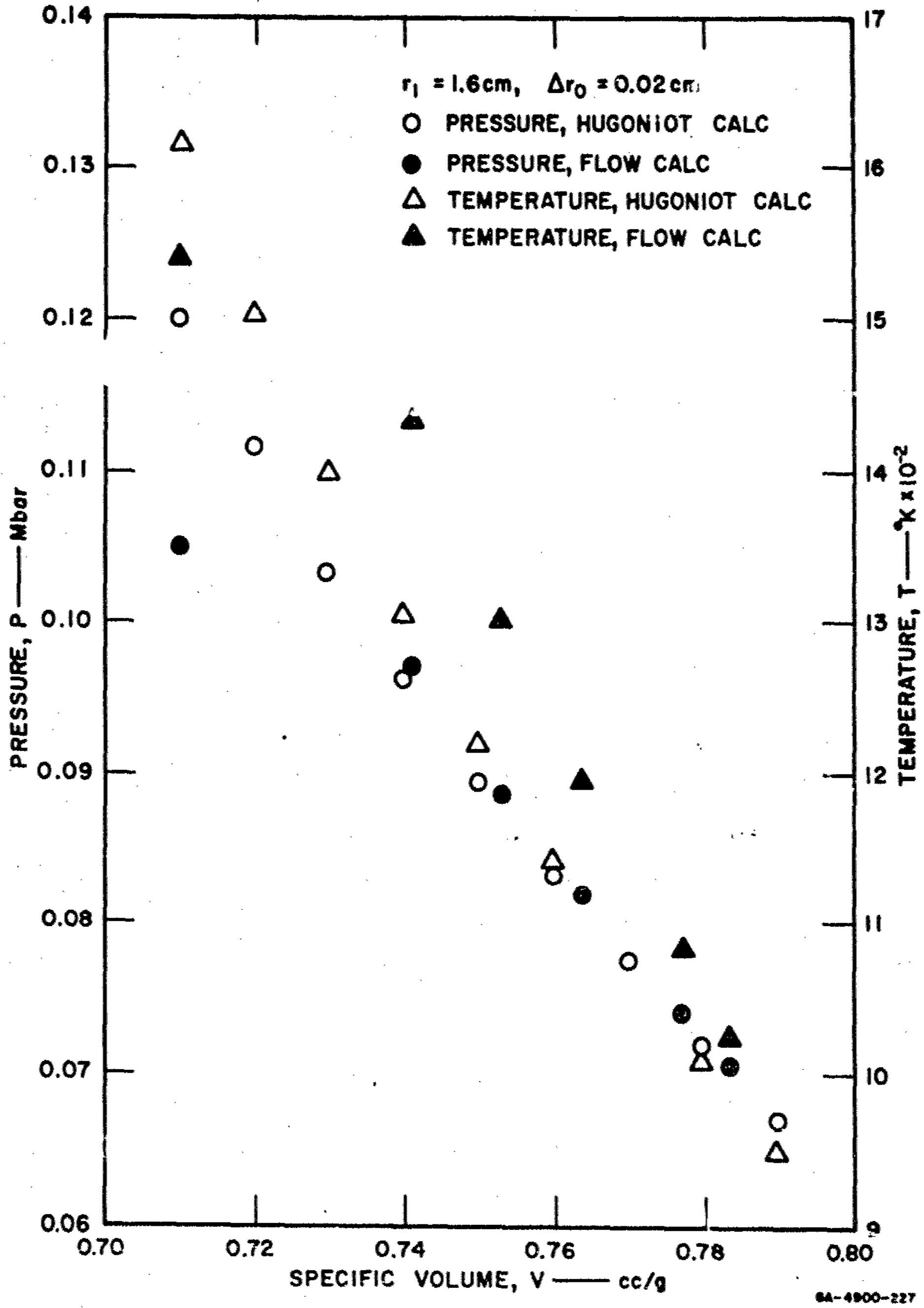

FIG. S4 ERRORS IN FLOW CALCULATION NEAR EXPLOSIVE-LIQUID INTERFACE, ETHER

Table 85

WASTE HEAT FOR THE BOMBLET OF STR-3
(r_1 = 1.6 cm, Δr_o = 0.02 cm)

Liquid	W_{153}* (Mbar cc)	$\frac{W_{153}}{\text{Explosive Energy}}$
Glycerin	0.3921	0.280
Water	0.5119	0.365
Ether	0.4856	0.345

*W_{153} is the waste heat dissipated in all liquid cells for which $J \leq 153$ (i.e., for a bomblet radius of 3.84 cm).

III SCALING

In the absence of viscosity as well as other time-dependent stresses and body forces, the equations of hydrodynamics scale linearly with distance. If viscous stresses are significant only in the shock front and if the jump conditions are satisfied at the shock front, linear scaling is still valid. Explosive detonation will not scale below some critical dimension, depending upon the reaction rate process involved. If we suppose in the present case that the burster radius is increased from r_1 to r_1' and that the detonation and flow processes scale, then for any field variable (e.g., P), we have

$$P'(r', t') = P(\alpha r', \alpha t')$$

or (S3)

$$P'(\frac{r}{\alpha}, \frac{t}{\alpha}) = P(r, t)$$

where

$$\alpha = r_1/r_1' = t/t' \qquad (S4)$$

and r' and t' are radius and time in the scaled problem, for which the pressure is P'.

Since waste heat is uniquely determined by the shock pressure, we should expect that

$$W_H'(r', t') = W_H(\alpha r', \alpha t') \qquad (S5)$$

Since radial zoning index, J, is a convenient space parameter we will sometimes use it in place of r. For $r > r_1$, we have

$$r_o = r_1 + \Delta r_o (J - J_I)$$

$$r_o' = r_1' + \Delta r_o' (J' - J_I') \qquad (S6)$$

Then if $\Delta r_o' = \Delta r_o$, $J = \alpha J'$, and $J_I = \alpha J_I'$, where J_I is cell number at the interface, we have

$$r_o = \alpha r_1' + \Delta r_o' (J - \alpha J_I') = \alpha r_o' \qquad (S7)$$

as before. When $\Delta r_o' \neq \Delta r_o$, but $r_1 = \alpha r_1'$ and $r_o = \alpha r_o'$, Eqs. (S6) yield

$$J - J_I = \alpha \frac{\Delta r_o'}{\Delta r_o} (J' - J_I') \qquad (S8)$$

Then

$$P' \left[(J' - J_I'),\ t' \right] = P \left[\alpha \frac{\Delta r_o'}{\Delta r_o} (J' - J_I'),\ t \right] \qquad (S9)$$

or

$$P' \left[\frac{\Delta r_o \ (J - J_I)}{\alpha \Delta r_o'},\ t' \right] = P \left[(J - J_I),\ t \right] \qquad (S10)$$

The total waste heat, W, can also be calculated from the scaling law. By definition,

$$W(r_o) = \int_{r_1}^{r_o} 4\pi r_o^2 \ \rho_o \ W_H(r_o) dr_o \qquad (S11)$$

Substituting $r_o = \alpha r_o'$, $r_1 = \alpha r_1'$, $W_H(\alpha r_o') = W_H'(r_o')$ into this yields the expression

$$W(\alpha r_o') = \alpha^3 W'(r_o') \qquad (S12)$$

$$W(r_o) = \alpha^3 W'(r_o/\alpha) \qquad (S13)$$

We expect, then, that P, W_H, and W will scale, provided the jump conditions are satisfied, the explosive detonation routine scales, and the interface calculation scales. The validity of the scaling assumption is illustrated in Figs. S5 through S7 and in Table S6. In addition, Figs. S5 and S6 illustrate the effect of decreasing zone size, Δr_o. It is seen to be negligible here and is assumed to be negligible in the rest of the calculations.

Figure S7 shows scaling of pressure to be valid also for ether (which is the worst case) except very close to the explosive. In view of other errors near the interface, this is not important for the present purpose. The application of Eq. (S13) to glycerin and ether is shown in Table S6.

Scaling was not tested for water and is assumed valid, since it is for the other two materials.

The near equality of W and $\alpha^3 W'$ in Table S6 and the close agreement between P and P_{scaled} and W_H and $W_{H\ scaled}$ in Figs. S5 through S7 are adequate bases for assuming that linear scaling with explosive radius is valid for the spherical bomblets of interest. On this assumption, Table S7 has been constructed.

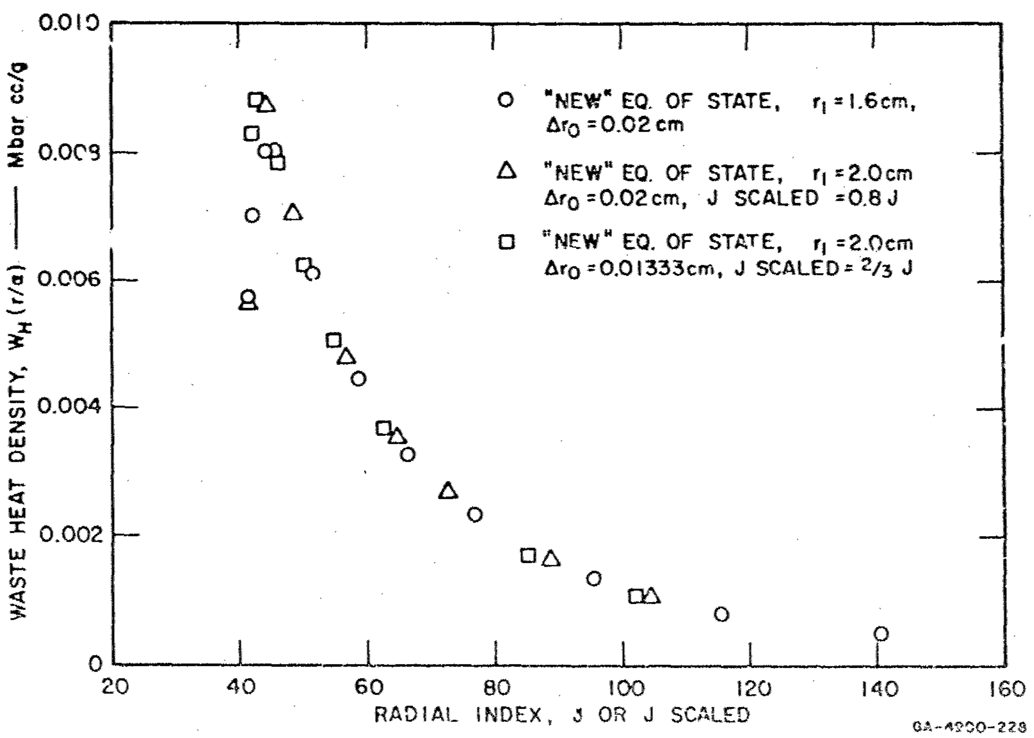

FIG. S5 SCALING OF WASTE HEAT DENSITY IN GLYCERIN

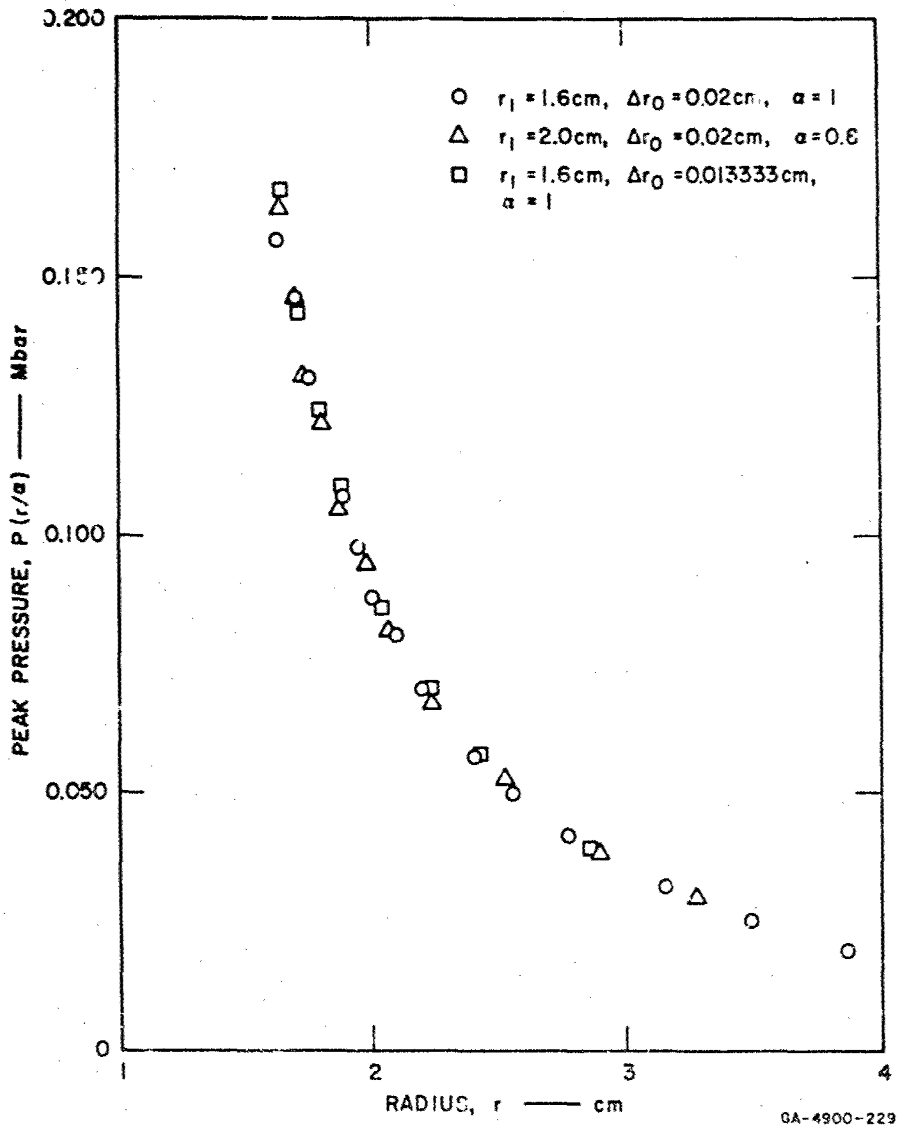

FIG. S6 SHOCK PRESSURE DECAY AND SCALING IN GLYCERIN

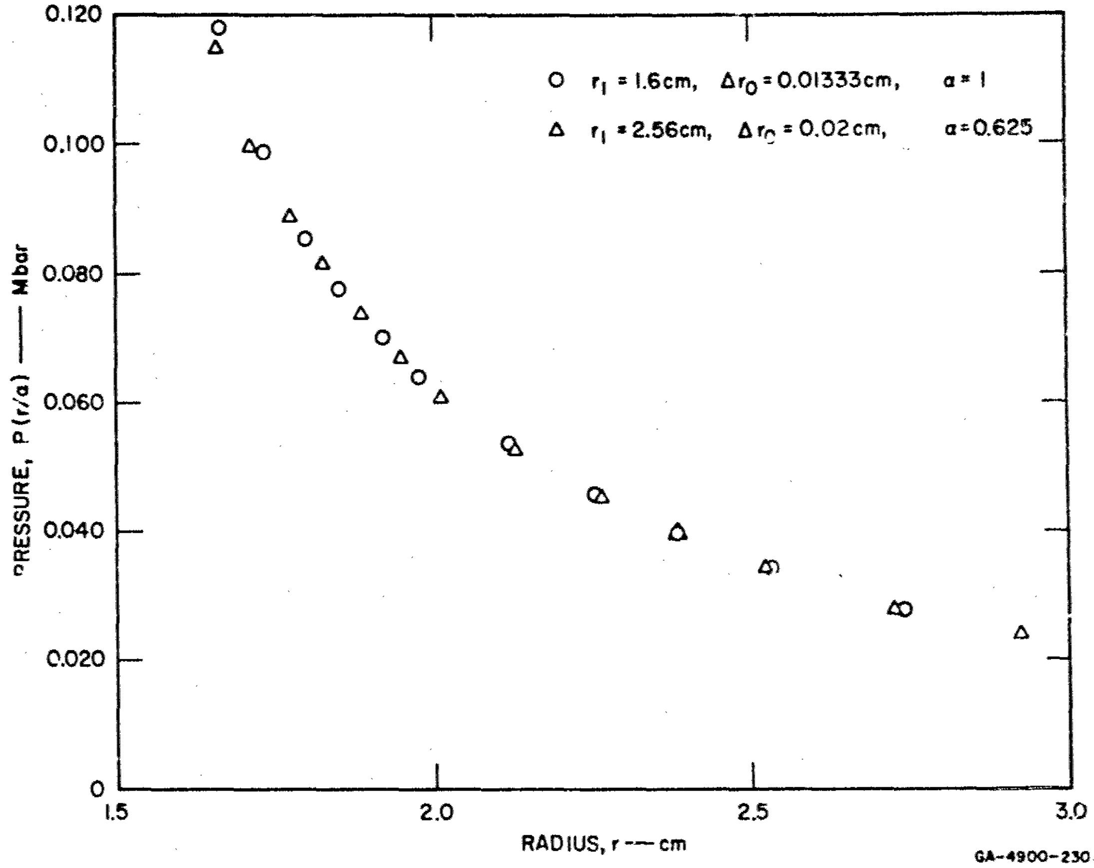

FIG. S7 DECAY AND SCALING OF PRESSURE FOR ETHER

Table S6

SCALING OF TOTAL WASTE HEAT*

$[r_o = (1.6/\alpha) + 0.02$
$(J' - 41/\alpha)$ (cm)$]$

Liquid	$J' = J/\alpha$	α	$J = \alpha J'$	W(J) (Mbar cc)	W'(J') (Mbar cc)	$\alpha^3 W'(J')$ (Mbar cc)
Glycerin	154	0.8	123.2	0.3291	0.6464	0.3309
Ether	257	0.625	161	0.490	2.013	0.491

*The close agreement between W(J) and $\alpha^3 W'(J')$ demonstrates the validity of the scaling approximation.

Table 87

WASTE HEAT FOR SELECTED BOMBLETS

r_1 = explosive radius, cm; $\alpha = 1.6/r_1$; E_e = explosive energy, Mbar cc

Δr_o = cell size; J = cell index; $r_2(J)$ = inner radius of Cell J, cm

W(J) = waste heat within and including Cell J

W/E_e = fraction of explosive energy absorbed in waste heat

J	r_2 (cm)	Glycerin		Water		Ether	
		W(J) (Mbar cc)	W/E_e	W(J) (Mbar cc)	W/E_e	W(J) (Mbar cc)	W/E_e
$r_1 = 1.6$; $\alpha = 1$; $\Delta r_o = 0.02$; $E_e = 1.401$ Mbar cc							
51	1.82	0.0786	0.056	0.1166	0.083	0.0939	0.067
71	2.22	0.1791	0.128	0.2512	0.179	0.2130	0.152
91	2.62	0.2514	0.179	0.3436	0.245	0.3021	0.216
111	3.02	0.3073	0.219	0.4123	0.294	0.3731	0.266
131	3.42	0.3521	0.251	0.4656	0.332	0.4326	0.309
151	3.82	0.3888	0.277	0.5081	0.363	0.4812	0.343
153	3.86	0.3921	0.280	0.5119	0.365	0.4856	0.347
171	4.22	—	—	0.5429	0.388	0.5227	0.373
191	4.62	—	—	—	—	0.5587	0.399

J	r_2'* (cm)	Glycerin		Water		Ether	
		$W'(r_2')$ (Mbar cc)	W'/E_e	$W'(r_2')$ (Mbar cc)	W'/E_e	$W'(r_2')$ (Mbar cc)	W'/E_e
$r_1 = 2.0$; $\alpha = 0.8$; $\Delta r_o = 0.02$; $E_e = 2.736$; $\alpha^3 = 0.512$							
51	2.275	0.1535	0.056	0.2277	0.083	0.1834	0.067
71	2.775	0.3498	0.128	0.4906	0.179	0.4160	0.152
91	3.275	0.4910	0.179	0.6711	0.245	0.5900	0.216
111	3.775	0.6002	0.219	0.8053	0.294	0.7287	0.266
131	4.275	0.6877	0.251	0.9094	0.332	0.8449	0.309
151	4.775	0.7594	0.277	0.9924	0.363	0.9398	0.343
153	4.825	0.7658	0.280	0.9998	0.365	0.9484	0.347
171	5.275	—	—	1.0604	0.388	1.0209	0.373
191	5.775	—	—	—	—	1.0912	0.399

J	r_2' (cm)	Glycerin		Water		Ether	
		$W'(r_2')$ (Mbar cc)	W'/E_e	$W'(r_2')$ (Mbar cc)	W'/E_e	$W'(r_2')$ (Mbar cc)	W'/E_e
$r_1 = 2.56$; $\alpha = 0.625$; $\Delta r_o = 0.02$; $E_e = 5.739$; $\alpha^3 = 0.24414$							
51	2.912	0.3219	0.056	0.4776	0.083	0.3846	0.067
71	3.552	0.7336	0.128	1.0289	0.179	0.8724	0.152
91	4.192	1.0297	0.179	1.4074	0.245	1.237	0.216
111	4.832	1.2587	0.219	1.6888	0.294	1.528	0.266
131	5.472	1.4422	0.251	1.9071	0.332	1.772	0.309
151	6.112	1.5925	0.277	2.0812	0.363	1.971	0.343
153	6.176	1.6060	0.280	2.0967	0.365	1.989	0.347
171	6.752	—	—	2.2237	0.388	2.141	0.373
191	7.392	—	—	—	—	2.288	0.399

*$r_2' = r_2/\alpha$

IV SCALING OF TABLE IX

The mass of liquid vaporized is calculated in STR-3 from the assumption that heat is mixed uniformly within a shell bounded by the explosive-liquid interface and the radius at which $W_H = h_B$ (the heat required to reach the boiling temperature). Referring to STR-3, page 40, we see that

1. J_B scales if Δr_o is unchanged, since W_H scales:

$$J_B' = J_B/\alpha \quad [\text{see Eq. (S7)}]$$

2. $M_B' = M_B/\alpha^3$

3. The heat required to boil M_B' is $(h_B + L_v)M_B'$

4. $W_B' = W_B/\alpha^3$ [see Eq. (S10)]

5. $M_v' = (W_B' - h_B M_B')/L_v = M_v/\alpha^3$ (S13)

That is, if $J > J_B$ and $J' > J_B' = J_B/\alpha$, then the mass of fluid vaporized under the present assumption is

$$M_v' = M_v/\alpha^3$$

when

$$r_1' = r_1/\alpha ,$$

provided space zoning is the same in both problems.

V CONCLUSIONS

For a given explosive and liquid in a spherical bomblet, specific waste heat scales linearly with the explosive radius. Total lost energy or waste heat thus increases as the cube of the scaling ratio, and the fraction of waste heat is independent of the scale, provided outer radius and explosive radius maintain a constant ratio. (These results are illustrated in detail in Table S7.)

For sufficiently small explosive radius (on the order of a few reaction zone lengths) scaling will fail because of rate processes in the explosive. For practical bomblets and high explosives, this failure is not apt to occur. If low explosives or propellants are used, it may be a serious problem; such a case would be operationally inappropriate, since it would signal an inefficient use of explosive.

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13. ABSTRACT

Special Technical Report No. 3 (hereafter referred to as STR-3) dealt with energy loss through shock heating in a bomblet with an explosive radius of 1.6 cm and an outer liquid radius of 3.85 cm. Detailed calculations were made for glycerin, water, and ethyl ether; the first and last representing practical extremes in the mechanics of organic liquid behavior. In this supplement, attention is focused on the effects of changing burster size. The validity of linear scaling is examined and is found to be adequate to burster radii of 2.56 cm. New equations of state are used for the three liquids mentioned above, and the sensitivity of waste heat to changes in equation of state is examined. In addition, an error introduced in STR-3 near the explosive-liquid interface by the numerical integration process is corrected.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Ether						
Water						
Waste heat						
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Burster						
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